Findings from the NESC Peer-Review of the Orbiter Debris Impact Analysis Capability, the DYNA Impact Damage Model, and Analysis-Test Correlation Procedure Used to Establish the Critical Damage Parameter

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Introduction:

From Jan 10 to Jan 14, 2005 the Orbiter Project Office, conducted a series of meetings to review the progress of tasks related to analytical assessment of debris impact to the orbiter. This review addressed all analytical tasks and tools, for preflight screening of critical debris (debris expected to be liberated by SSP elements), in-flight damage assessment and damage repair. In an attempt to ensure that there were no misunderstandings regarding analytical tool interfaces and flow of critical data, a significant amount of time was spent on the debris analysis process. The review also addressed some test data as it relates to modeling assumptions and correlation; however, testing, in general, was not a focus of this review.

NESC participation in the summit completed a peer-review of the DYNA impact analysis capability, the DYNA damage model, and the test-analysis damage correlation. The peer-review findings are presented below. The specific technical issues listed below were raised and discussed during the summit. **The formal action items from the summit accepted by the Program Problem Resolution Team address all the concerns raised by the NESC peer-review.**

General (G) Observations:

G-1. VERIFICATION: The amount of work still to be completed to have tools substantially complete and properly validated prior to RTF is significant. Schedules and/or plans for completion of many critical tool development and validation activities were not presented at the summit. The current level of tool maturity does not leave time for dealing with any significant test problems or correlation difficulties between now and the May RTF.

G-2. DOCUMENTATION: At this time, the documentation of debris analysis tool requirements, and documentation of analysis tools and results are inadequate to support "certification" of debris impact capability. There are no formally documented overarching, program requirements for the analytical models being developed. This lack of documented requirements puts the program at risk that there will be disconnects among the model development teams or between the analysis community and major stakeholders (program, SSMs, NSEs) in terms of expectations for tool performance and accuracy. The documentation associated with the tools and resulting assessments of structural capability are virtually non-existent. The direction from the program is for minimal documentation of tools prior to RTF. This lack of documentation is inconsistent with program requirements for complete validation and documentation of analytical products prior to establishing flight readiness.

G-3. UNCERTAINTY: Factor of safety requirements and uncertainty of results is an issue that the team has not resolved at this time. There is no means of conducting end-to-end verification of this complicated analysis process. Furthermore, the component level test plan is limited in scope and number of tests. While a best effort is made to correlate individual models, there is an opportunity for build up of uncertainty across these many interfaces, the end result of which is an analytical methodology that is not predictive of true vehicle performance.

Observations/Concerns/Issues about the Orbiter Tile (T) Impact Analysis (NESC POC: Julie Kramer-White)

T-1. Definitions of "impact tolerance" and "damage tolerance" for tile are not universally understood. Current SE&I definition of "impact tolerance" is NO DAMAGE or change in configuration, which for tile includes no coating damage. This is contrary to early analysis definitions and this difference is still apparent in analysis products.

T-2. Tile damage models and the algorithms for cavity predictions are only valid for damage predicted to be shallower than the densification level. The physics and resulting damage changes significantly when there is enough energy to penetrate beyond the densification layer; therefore models are no longer valid.

T-3. All tile models are at various levels of maturity and validation. Some have had some preliminary validation conducted, but are scheduled to have upgrades in capability (i.e., replacement of 2D sintering models with 3D sintering models, improved RTV debond models, etc.). Process needs to ensure that final versions of analytical models go back through appropriate correlation and validation processes. Like RCC, tile analytical tool developers must be extremely careful to differentiate between model development tests, and true validation tests.

T-4. Recent tile impact testing has shown a previously unknown tile failure mode (shear to densified layer with subsequent loss of majority of tile). It is unknown at this time, how this failure mode will be dealt with in tile damage predictions, as this failure mode is not currently modeled.

T-5. Preflight screening generates a nominal and bounding cavity dimension for a damage site based on test data. The bounding cavity is intended to be bounding for width and length, but only 95% confidence on depth.

T-6. The prioritization of modeling activities for special configuration and penetration areas is not based upon any assessment of likelihood or criticality of impact; therefore models for vertical tail are complete, while critical areas such as the MLG door and ET doors are only partially complete, and elevon cove have not been started. However, it is anticipated, at this time, that all models will be completed prior to RTF.

T-7. It appears there may be some issues, such as wormholes and aft face slumping, that can only be predicted with better fidelity geometry of this aft cavity face.

T-8. Proper correlation of the thermal math models requires extensive comparison and correlation to arc-jet testing; however, aerothermal only has 'bump' factors for the arc-jet for depths to 0.5 in. Therefore, correlation of thermal math models is going to require that 'bump' factors be determined for deeper depth damage in the arc-jet.

T-9. The only programmatic requirement identified in the process review was a requirement for the process to be able to analyze 10 "damage sites" in 24 hours; however, "damage site" could mean one crater, or multiple craters (models) required for a single debris event. This inconsistency could result in many more than 10 models being required in a 24 hour period. The final analysis product is not well defined. Having analyzed the event could imply an initial pass with very conservative entry trajectory parameters to select critical cases, which will require further mission specific analysis. Multiple trajectories or other parametric studies required to clear these cases will result in many runs on any given model. "Damage site" and analysis expectations need to be better defined in programmatic requirements to ensure that tools and process meets program expectations.

T-10. An "uncertainty tree" was presented as an attempt to understand the variability that each input brings to the final analysis. It is not clear how this uncertainty "analysis" will be utilized, nor how it will be validated. Someone should lay out a plan for how end-to-end uncertainty is going to be dealt with in this analysis to ensure that this exercise produces a useable input. Some senior level review of the value of this uncertainty stack up process and the utilization of such data may be warranted.

<u>Observations/Issues/Concerns about the Orbiter WLE RCC (R) Impact Analysis</u> (NESC POC: Ivatury S. Raju)

R-1. The DYNA team is able to correlate measured deflections reasonably well but is having a difficult time with correlating measured strains. The difficulty with strains is attributed to craze cracking of the SIC coating. With regard to the deflections, the correlation at the center of the impact is not good and the correlation improves as one moves away from the center of the impact. A detailed analysis of the recent RCC component tests needs to be thoroughly performed to understand any discrepancies.

R-2. Limited Arc-jet testing and analytical results shows that 0.020 in. x 0.020 in. surface coating loss with an accompanying delamination will result in a burn-through at the critical locations of the WLE RCC. The test program did not establish the critical size for the delamination. The limited test data show that coating loss is always accompanied by delamination at the midplane of the C-C substrate. More test data may be necessary to establish this damage size as the requirement for impact damage tolerance. In addition, the NDE community needs to assess the reliability of both ground-based and on-orbit inspection methods to reliably detect damage this small.

R-3. Based on the arc-jet burn-through test results, the program is moving from damage tolerance to impact tolerance. Impact tolerance is the ability to sustain impact damage and perform the intended functions without any change in the hardware configuration. Damage onset is currently viewed as the impact tolerance damage criterion. Therefore, the previously used damage criterion of a through-penetration, represented by 1 to 5 elements in the DYNA model with a damage parameter of 1.0, must be replaced with a criterion based on delamination onset and coating loss. This damage criterion is more difficult for the DYNA damage model to predict than was the through-penetration damage state.

R-4. The DYNA analysis approach uses shell elements to model the RCC and uses a damage model based on the concept of continuum damage mechanics. Neither shell elements nor the damage model can be used to predict delamination onset and growth. In addition, the damage model cannot predict surface coating loss. To overcome these deficiencies, the DYNA analysis approach must rely on an empirical (test-based) process to establish the value of the damage parameter that correlates to damage onset. Therefore, an extensive test program will be required to verify the <u>predictive</u> capability of the DYNA impact analysis methodology.

R-5. As stated in R-3, the DYNA analysis is being refocused to determine the onset of damage. The analysis team suggests that from all the experimental and analytical correlations conducted so far, damage onset occurs at a DYNA-calculated peak damage parameter of 0.9. This value is termed the critical damage parameter. Since the damage model cannot explicitly predict delamination initiation and growth or coating loss, additional tests may be required to verify that a damage value of 0.9 is valid for the onset of delamination. In addition, it should be noted that the damage model used in DYNA allows strains that far exceed the ultimate strain of the RCC. This condition may occur at values of damage well below 0.9. Further test-analysis correlation is required to verify that critical damage is not developing at values below 0.9.

R-6. The DYNA team explained that the SLIM and EROD parameters (used in the MAT 58 material model) were tuned to coupon test very early in their studies. These coupon tests were tension, compression, and shear ultimate strength tests. The values being used are: SLIMT=0.8, SLIMC=1, and ERODS=0.1. These values need to be confirmed as valid for the new damage criterion (delamination onset and coating loss).

R-7. The previously developed DYNA analysis methodology, using the through-penetration damage criterion (represented by 1 to 5 elements out), has been validated by correlating with a wide range of test data. This methodology can still be utilized for non-critical RCC regions where burn-through is less likely to occur.

R-8: A rapid response methodology called IMPACT2 was presented. A NASTRAN modal analysis of the RCC panels, including the foam impactor modeled as non-linear springs, is used to predict damage to the RCC during impact. The nonlinear spring stiffnesses are obtained by using the foam stress-strain curve. Stresses from the NASTRAN analysis (IMPACT2) are compared to a compressive stress allowable to determine damage in the RCC. Using a value of 21ksi for the compressive stress allowable, the IMPACT2 damage results correlated to within 15% of the DYNA analysis results. (The Vought material properties report shows a compressive allowable stress of 20-25 ksi). The accuracy of the IMPACT2 method needs further verification by comparison to all the available impact test data.

Concluding observation (based on the current limited test and analysis results):

The team developing the impact analysis methodologies is following good engineering practices in developing and validating the models. The NESC has noted some areas where the models can be improved and has provided these recommendations to the teams. They have been incorporated into the formal actions from the Analysis Summit, and are expected to be addressed at the upcoming Orbiter DCR, and closed out prior to FRR.

The concern of the NESC reviewers is that given the limitations of impact analysis models and given the large amount of work still to be done in testing and correlation, the Program will not have time to adequately validate and document the models prior to a May flight. It is likely that the engineering approach currently being developed will result in an impact tolerance capability (C) which will be lower than the expected debris environment (E) for some debris cases. Due to large uncertainties, this analytical methodology may not be predictive of true vehicle performance (the prediction is conservative with respect to airframe structural integrity).

Approval and Document Revision History

Approved: Original signed on file — 2/11/05

NESC Director — **Date**

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